Biomechanical energy harvesting from human motion: theory and applications

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Abstract

Background

Biomechanical energy harvesting from human motion presents a promising, clean alternative to electrical power supplied by batteries. This technology could provide electrical power for portable electronics devices, for computerized and motorized prosthetics. In this study investigate the amount of energy that could be harvested from the following human motions: heel strike; ankle, knee, hip, shoulder, and elbow joint movements; and centre of mass motion during walking. We seek to harvest energy while adding only minimal effort to the user.

Methods

Evaluation of major motions during walking is performed; this analysis is based on identifying how much work is done during the motion, and what part of it could be used with adding minimal effort. E.g. During a heel strike energy is lost to the surroundings through the compression of the shoe sole. In joint motions there are phases where the muscles act as brakes, and where the required braking torque could be replaced by an electrical generator. The amount of energy that could be harvested is estimated with tools used to study human motion, such as inverse dynamics.

Results

The analysis reveals that for a device that uses centre of mass motion the maximum amount of energy that could be harvested is approximately 1W per kg weight of the device. For an individual with a weight of 80kg walking at normal speed the power generation from the heel strike, is approximately 2W. Further, for a device based on regenerative braking that is mounted on a human joint, the most powerful joints are knee, 34W, and ankle, 20W.

Conclusions

These theoretical calculations align well with current devices performance and they also suggest that much more energy could be harvested from the lower limb joints. However, to do so an innovative and light mechanical design is needed. For better understanding of the weight issue, we compared the option of carrying batteries to the cost of harvesting the energy. Further, advantages of methods for conversion of mechanical energy into electrical energy are described. Lastly, currently all devices apply either maximal torque or no load. We concluded that regulating joint resistance load should enable better power output.

Background

With the increasing use of portable electronics devices such as mobile phones, the GPS (global positioning system), and laptop computers in our daily lives, the need for mobile electrical power source is increasing. This power demand is typically answered by carrying batteries for the operation of these devices. This, however, limits the time of use of these devices as the batteries run out and need to be recharged or replaced. For general use in the western world this problem is more of an inconvenience, and it and can be solved by connecting to the electrical grid. For some users this solution is not feasible, such as users in third world countries and hikers who travel in remote areas where the power grid is not well developed or stable. Other examples for such a need are: computerized prostheses such as the Proprio foot, Rheo Knee, and C-leg, which need to be charged at least every two days and have an average power consumption of less than 1 W [1-3]. A more power-demanding application is the Power Knee, which is a powered prosthesis for above-knee amputees with actuation. The Power Knee needs to be recharged after every six hours of continuous use [4]. In all the above applications the operation time is limited by the

ability to carry the weight of the batteries and therefore there is a need to compromise in terms of the amount of electrical power and time of usage.

Technology that will provide energy for a longer time without having to recharge the batteries is required. There have been many developments of batteries with better power density and optimization of power usage, as well as searching for alternative sources of energy such as solar and fuel cell technologies. An interesting technology that has the potential to generate energy to power electrical devices is using human body motion.

The idea of harvesting energy from human motion is based on the fact that an active person's energy expenditure, which is the amount of energy used by the body, is $1.07*10^7$ J per day [5]. This amount of energy is equivalent to approximately 800 AA batteries of 2500 mAh, whose total weight is about 20 kg. A considerable amount of this energy is released in the form of heat and motion. The mechanical efficiency of the human body is estimated to be about 15-30% [6]. Hence, we might be able to use this energy for powering electronics devices in addition to generating motion.

The main challenge in developing such technology is to construct a device that will harvest as much energy as possible but will interfere only minimally with the natural motion of the body. Further, ideally such a device should not increase the metabolic cost, which is the amount of energy required by the human to perform the activity.

As mentioned above, human mechanical efficiency is at most 30%. This means that most of the energy humans consume as food is released into the atmosphere as heat. Hence it would make sense to try and harvest this thermal energy and convert it into electrical energy. However, there are several obstacles to overcome in order to utilize this thermal energy. First, based on Carnot's equation [7] it is

possible to calculate the maximum efficiency of a heat engine device. A heat engine is a device that converts heat energy into mechanical energy. At a supposed environment temperature of 20ºC, the best efficiency of such system will be

$$\text{Efficiency}=\frac{T_{Body}-T_{Ambient}}{T_{Body}}=\frac{310-293}{310}=5.5\%\,, \quad (1)$$

where T_{Body} and $T_{Ambient}$ are the body and the surrounding temperatures in Kelvin degrees. During natural walking the total energy that is released into the atmosphere as heat is approximately 300W [5]. If we could convert all this energy into electricity with the maximum calculated efficiency, the maximum power available during walking would be 16.8W. However, in order to achieve this, the entire human body would have to be covered with a suit, and this might not be practical. Further, in a warm climate the temperature difference between the body and the surrounding environment will be lower, which will reduce the efficiency of the heat engine device.

This leads us to focus on the mechanical energy of the body during motions performed while walking. Complex motions such as walking and running are composed of many relative motions between different body segments, e.g., forearm and upper arm, or between a segment and the ground, e.g., heel strike and centre of mass. When considering a given motion as a candidate for an energy harvesting device, the main factors that need to be taken into account are as follows. First, during walking the muscles cyclically perform positive and negative mechanical work within each stride. Where during positive work phase the muscles generate the motion, in negative work phases the muscles absorb energy and act as brakes to slow or stop the motion [6]. Ideally the energy harvesting device will replace the muscle action during negative work and create the resistance to slow the motion, similar to “generative braking” in hybrid cars. Therefore when assessing the potential power harvesting

capability during each motion, we should focus on the muscle's negative work phases. A second factor is the effect the device may have on the human gait. As an example, during the heel strike part of the energy is converted into heat in the shoe sole [8]. Therefore harvesting this energy should not affect normal gait pattern. Third, an important parameter for the energy harvesting device is how the device will be attached to the human body and how convenient its use will be. A final factor is the effect of the additional weight of the device on the amount of human effort. In the following section we analyze the main human body motion segments during natural walking to assess the potential power harvesting capability during each motion segment.

Methods

For the analysis of the energy during these motions we used the following definitions of work: 1) force acting through a displacement, and 2) the product of torque and angular displacement.

$$W = \int_0^s F \cdot ds \text{ and } W = \int_0^\theta \tau \cdot d\theta, \qquad (2)$$

where we denote the force and torque as F and τ, and the linear and angular displacements as S and θ.

Negative and positive muscle work: Winter [6] defined negative and positive muscle work as follows. Positive work is the work performed by the muscles during a concentric contraction, that is shortening of the muscle, when the torque applied by the muscle at the joint acts in the same direction as the angular velocity of the joint. When the muscle is performing positive work, it generates motion. Negative work is the work done during an eccentric contraction, i.e., lengthening of the muscle, when the muscle torque acts in the direction opposite to the angular velocity of the

joint. When the muscles conduct negative work they act as brakes to slow or stop the motion. An equivalent term for negative work by the joint muscles is energy absorption. In this case the energy absorbed by the muscle is released in the form of heat, causing the muscles to get warmer.

The major body motions during walking that will be considered as potential energy sources are heel strikes, centre of mass motion, shoulder and elbow joint motion during arm swings, and leg motions, i.e., ankle, knee, and hip motions. Next we analyze each of these motions and estimate the amount of work performed at the relevant joints and locations.

Heel strike

Heel strike refers to the part in the gait cycle when the heel of the forward limb makes contact with the ground. Several studies have modelled this motion as a perfect plastic collision, e.g., [9]. Other researchers believe that there is an elastic component to this motion, e.g., [10, 11]. It is, however, generally agreed that there is energy loss during the collision.

Several researchers have studied this motion and tried to estimate the amount of energy it dissipates. For example, Shorten has calculated the energy loss in a running shoe, and relates it to force acting through a linear displacement [11]. Using a viscoelastic model for a midsole, he found out what part of the energy is stored as elastic energy at the shoe sole and what part is dissipated. He predicts that for a typical runner running at 4.5 m/s the value of dissipated energy could range from 1.72 to 10.32 J during a single step, while most of this energy loss occurs during the heel strike. For a better understanding of the source of energy, let us consider a simple model where an external force is acting on the shoe sole during a gait cycle (Figure 1). The maximum ground reaction force acting on the shoe is approximately equal to

1.2 of the body weight, and most of the heel compression occurs directly after the heel strike (first 20% of the gait cycle). Therefore, assuming displacement of 4 mm in the shoe sole and a weight of 80kg, the work for the compression of the heel is approximately 2 J/step. Since a gait cycle is approximately 1Hz at walking (two steps per second), the theoretical maximal power will be 4W. Moreover, if 50-80% of the energy is stored as elastic energy in the shoe [11], then the maximum energy during walking that is available for use would be approximately 2W. While it is possible to construct a device that will have a larger displacement during the heel strike, this may lead to declining stability and maneuverability [12]. Intuitively speaking, this will result in a feeling such as of walking on soft sand.

<< Figure 1 should be inserted about here>>

Leg motion

During walking, a human’s muscles generate movements at the ankle, knee, and hip joints. These torques are all along three axes (3-D) and their magnitude changes during the gait cycle (Figure 2). However, the most significant torque in term of the work that is performed during the walking cycle is the movement that is normal to the Sagittal plane [13]. Winter and colleagues calculated the work performed at leg joints during one step and normalized it by the subject’s weight [14]. In addition, they divided the net work done by the muscles at the joints into several phases of motion. The classification is based on muscle negative energy and positive energy performed during walking (Table 1). We have used these findings to estimate the total and negative work done during a gait cycle at the hip, knee, and ankle joints.

For an 80 kg person during natural speed walking where the general form of the equation used for the calculations is:

$$\frac{Work}{setp} = Weight \times \left[\left| \text{phase}_1 \right| + \left| \text{phase}_2 \right| + \ldots + \left| \text{phase}_n \right| \right] = \frac{J}{setp} \quad (3)$$

<u>Energy calculation for the ankle</u>

$$W_{total} = 80 \times \left[\left| -0.0074 \right| + \left| 0.0036 \right| + \left| -0.111 \right| + \left| 0.296 \right| \right] = 33.44 \frac{J}{setp}$$

$$W_{negative} = 80 \times \left[-0.0074 - 0.111 \right] = -9.47 \frac{J}{setp}$$

$$\frac{W_{negative}}{W_{total}} = \frac{9.47}{33.44} = 28.3\% \quad (6)$$

Energy calculations for the knee

$$E_{total} = 80 \times \left[\left| -0.048 \right| + \left| 0.0186 \right| + \left| -0.047 \right| + \left| -0.114 \right| \right] = 18.2 \frac{J}{setp}$$

$$E_{negative} = 80 \times \left[-0.048 - 0.047 - 0.114 \right] = -16.72 \frac{J}{setp}$$

$$\frac{E_{negative}}{E_{total}} = \frac{16.72}{18.2} = 91.9\%$$

Energy calculations for the hip

$$E_{total} = 80 \times \left[\left| 0.103 \right| + \left| -0.044 \right| + \left| 0.090 \right| \right] = 18.96 \frac{J}{setp}$$

$$E_{negative} = 80 \times \left[-0.044 \right] = -3.52 \frac{J}{setp}$$

$$\frac{E_{negative}}{E_{Total}} = \frac{3.52}{18.96} = 18.56\%$$

To sum up, the total work done at the hip is 18.96 J, while its negative portion is 3.52 J. For the knee, the total work is 18.2 J, and the negative portion is 16.7 J. For the ankle, the total energy is 33.4 J and the negative portion is 9.7 J.

<< Figure 2 should be inserted about here>>

<< Table 1 should be inserted about here>>

Arm and centre of mass

In order to calculate the energetics of the arm and the centre of mass, we preformed an experiment with three male subjects (weight: 82kg [range 72-88 kg]; height: 180 [range 1.72-1.86m]), who walked at natural speed 1.1 m/s (range 1.0-1.2m/s). Motion data were obtained using a six-camera motion capture system with a sampling rate of 100Hz (Vicon 460, Lake Forest, CA). Marker motion data were low-pass filtered (Butterworth fourth-order forward and backward passes) with a cut-off frequency of 6 Hz. The arm was represented by a tow link system consisting of upper arm and forearms (including the hands). The segmental properties (mass, centre of mass and moment of inertia) were calculated based on adjustments to Zatiorsky-Seluyanov's work by De Leva [15].

Centre of mass motion

Another motion that could be utilized to generate energy is the motion of the centre of mass. The centre of mass performs a motion similar to a 3-D wave (i.e., up-down and left-right). The amplitude of the vertical wave is approximately 2.5cm (total motion from lowest point to highest is 5cm) [6]. Alexander estimates the energy required for human motion as the energy required to redirect the velocity of the body centre of mass at the end of each stride [16]. Based on an inverted pendulum model (Figure 3) that consists of a point mass moving on a rigid mass-less leg, he proposed that the velocity of the centre of mass just before the changeover is at a right angle with the leg (-V), and after the changeover it is at a right angle to the leading leg (+V). He argued that there is a loss and regain of vertical kinetic energy. In order for this change in velocities to occur, the leg muscles need to do negative work and then an

equal magnitude of positive work. He proposed an equation for the cost of transpiration based on the above. We used this model to estimate the cost of transportation for a mass located near the body centre of mass.

$$C = \frac{V^2}{4gl} \times Sin(\theta), \quad (3)$$

where C is the cost of transport (work per unit of body weight and travel distance); -V is the velocity immediately before the cross-over between legs occurs, and +V is the velocity after the cross-over; l is the leg length; θ is half the angle that one leg conducts during full step.

Using this model and the experimental data from three test subjects, we calculate the energetic cost of transporting a 20kg payload mounted on the centre of mass for a 1.80m person during walking at speed of 1.1 m/sec. Where the velocity before and after (V) was approximately 1.3m/s, the average step length was 1.3 m, leg length was approximately 1m, and the gait cycle frequency 1Hz. From trigonometry we can see that the angle θ is approximately 40^o. Therefore the cost of transportation C =0.028 and the energetic cost for carrying a 20kg mass is 5.4J per step and 10.8 W, respectively.

The second model we used for estimating an upper bound for the total amount of energy required to generate this motion is based on changes of height of the mass at each gait cycle (i.e., the mass moves up and down approximately 5 cm each cycle). Assuming no exchange of kinetic and potential energy, we can assume that the energy required moving the mass one gait cycle would be: E=mgh, where E is energy, m is mass, g is the gravitation acceleration, and h is height. Based on previous walking data (20 kg mass, etc.), we can produce 20W if we could harness this energy.

<< Figure 3 should be inserted about here>>

Arm motion

Arm motion refers to the swing movement of the arm backward and forward during walking and running. The arm motion is composed of two sub-motions, the relative motion between forearm and upper arm (change of angle in the elbow), and the relative motion between the trunk and the upper arm (change of angle in the shoulder).

To calculate the net muscle joint torque during the during the gait cycle, we used a recursive inverse dynamic (top down). Then, using equation 2, we calculated the work at the shoulder and elbow joint during a gait cycle.

Results

Maximal amount of energy

All our analyses are summarized in Table 2. This summary presents the amount of work performed in each joint or body part and how much of it is negative work. Further, it shows the maximum joint torque during these motions. This is important, since for harvesting maximum energy, our energy conversion device should be able to withstand torques similar in magnitude.

<< Table 2 should be inserted about here>>

When considering the design of the energy harvester, this device will ideally be able to generate electricity from human motion without causing additional load. Analysis of human motion reveals that there are two types of motion that are relevant for harvesting energy: 1) motions where the energy is lost to the surroundings (e.g., heal strike), and 2) motion where the muscles are performing negative work. In a motion such as the heal strike, the energy can be lost in the form of heat, plastic

deformation, sound, or any other form. Since this energy is lost in any case, using it for an energy conversion device will not cause additional load to the user. The second type of energy source is phases in the motion where negative work is done by the muscles. The idea is that during these phases the muscles are acting as brakes and slow down the motion of the limb. By replacing the work done by the muscle with an electric generator we could reduce the load on the muscles and generate electricity at the same time, similar to generative breaking in hybrid cars. Other factors that need to be considered are that the weight of the device will increase the energy expenditure, and that the lower the additional mass mounted on the leg, the more the energetic cost of carrying will increase [17, 18].

Cost of harvesting electrical power

An addition of mass to the device adds to the metabolic cost of using it. In addition to the weight, the location of the device is also important. As the metabolic cost for carrying the load becomes higher, the lower the mass is placed on the leg [17, 18]. Therefore, when comparing two devices that weigh the same and produce the same amount of energy, a knee device will have a better COH [19] than an ankle device, where the cost of harvesting (COH) is defined as:

$$COH = \frac{\Delta metabolic\_power}{\Delta electrical\_power}. \tag{4}$$

Moreover, currently both the knee device and the backpack increase the metabolic power; in theory if the weight of the devices is small enough it is possible that they will not increase the metabolic cost. Therefore, reduction of the device weight by the use of lighter materials (e.g., carbon fibres) and an optimized design could have a significant effect on the shoe and the knee devices' COH. Another important aspect is the relation between the metabolic power and the electrical power generated, where the total metabolic cost is constructed form the metabolic cost of

positive and negative work at the joint. Yet, the efficiency of the muscle during these two types of muscle work is not the same.

For positive work, efficiencies range between 15% and 25% [6], while for negative work the muscles' efficiency values range from 28% to 160% [20, 21]. The parameters that affect muscles efficiencies are: the performed motion, the muscles involved, forces, and velocity. This means that when the energy harvester replaces the muscle work during negative work, the predicted reduction in metabolic cost will be less then the predicted reduction for replacing positive work phases. Further, in some case the negative work is performed using passive elements such as connective tissue, which store elastic energy like spring and returns it back [22]. In these cases harvesting this energy means that the muscles will have to perform extra work in order to return the energy that is lost to the device. Furthermore, for devices based on the generative braking we have used the joint net power as a criterion to determine joints that are good candidates for energy harvesting devices. Yet, it is difficult to interpret the contribution of each muscle to the net joint torques. This is due to several reasons: 1) Muscles are working at cross multiple joints, and therefore theoretically it is possible that the muscle will contribute to negative work at one joint and positive work at the other joint; 2) The net joint moment results from all agonist and antagonist muscle activity, and therefore cannot account for simultaneous generation of muscle group and absorption by the antagonist group, or vice versa. As a result it is possible that when the generator resists the motion during positive power it will help the muscle that is doing negative work. Therefore, when recommending an appropriate joint for the generative braking based on the amount of negative work done at the joint, it should be considered as a predication and be evaluated based on experimental work.

Comparing the cost of energy harvesting to carrying batteries

While ideally the energy harvesting device would not increase the metabolic cost, in some cases it might. In these cases individuals may have to carry extra food in order to cover the additional metabolic cost due to electricity generation. Hence, for a given mission, a comparison should be made between the metabolic cost for generating energy and carrying the extra food versus carrying batteries with the equivalent amount of energy, in order to decide what the best option is. In the case of the backpack device [12] the user carries the food and the batteries on his/her back so that the cost of the carrying the weight is the same. This device achieved 19.5% efficiency in converting the metabolic energy to electrical power. The specific energy of food is typically (3.9×10^7 J kg^{-1})[23], which is much greater than specific energy for lithium batteries (4.1×10^5 J kg^{-1}) and zinc-air batteries (1.1×10^6 J kg^{-1})[24]. Therefore, when comparing the need to carry extra food versus the batteries the weight of food will be 19 times lighter than lithium batteries and 7 times lighter compared to zinc-air. For example, walking at 1.5m/s (while generating 5W) for 10 hours will save approximately 0.4kg of lithium batteries and 0.15kg of zinc-air batteries, meaning the longer the expedition, the greater the weight savings.

While for the backpack most of the weight is carried anyway, the knee device adds extra weight to the user; further, its location on the knee causes a higher metabolic cost than a weight that is added at the back or waist. This additional weight explains why, although this device has a better COH, its conversion efficiency of 7.6% is lower. However, better and lighter designs should increase this device's conversion efficacy significantly.

Discussion

After developing a better understanding of the energy sources from human motion, we include a state-of-the-art review of existing devices. These devices are

classified according to the motions used to harvest the energy and the location of the device on the body.

Centre of mass

This is a device based on the motion of centre of mass during walking. These types of devices use the motion of the centre of mass relative to the ground to generate energy. Due to this motion the body applies forces on the backpack or any other mass in order to change the direction of its motion. Rome and colleagues used these forces in a spring-loaded backpack that harnesses the vertical oscillations to harvest energy [12]. This device, with a 38 kg load, generates as much as 7.4W during fast walking (approximately 6.5 km/h). The device is a suspended-load backpack (Figure 4) that could be interposed between the body and the load, resulting in relative motion movement. In this device the relative motion was approximately 5cm and this linear motion was converted to a rotary motion that drove a generator (a 25:1 geared dc motor). Generating this energy was achieved with a small amount of extra metabolic cost of 19W, which is 3.2% more than carrying a load in regular backpack mode (with no relative motion).

<< figure 4 should be inserted about here>>

Another approach to harvesting energy using a backpack was taken by Granstrom and colleagues [25], who mounted a piezoelectric in the shoulder strap of 44Kg backpack and used the stress in the straps to create 50mW. Different classes of devices that use the motion of the centre of mass to harness energy are based on oscillations of a floating magnet due to this motion. Niu and colleague built a linear electrical generator (1kg) that used the motion of the body during walking to produce from 90 to 780mW, depending on the walking conditions [26]. In this study they

optimized the electrical circuits and linear generator design to produce the highest power output from the walking motion.

Heel strike

Several devices have been built in the past to generate energy from the heel strike motion. These devices use the energy from the relative motion between the foot and the ground during the stance phase (the phase in which the foot is on the ground). In addition, in some cases the device uses energy from the bending of the shoe sole. In both cases the device aims to use energy that otherwise is lost to the surroundings. An example of such a device is a hydraulic reservoir with an integrated electrical magnetic generator that used the difference in pressure distribution on the foot to generate a flow during the gait cycle. This prototype produced an average power of between 250 and 700 mW during walking (depending on the user's gait and weight). However, it was quite bulky and heavy [27]. Paradiso and his colleagues built a shoe that harvested energy using piezo-electrical materials from heel strike and the toe off motions.**.** The average power during a gait cycle was 8.3mW. Another device that was built by the same group is a shoe with a magnetic rotary device that produced a peak power of 1.61 W during the heel strike and an average power of 58.1 mW across the entire gait [28].

A different approach was taken by Kornbluh and his collaborators [29] at SRI International, who have developed electrostatic generators based around *ElectroActive Polymers.* This material can generate electricity as a function of mechanical strain. This technology enables energy densities for practical devices of 0.2 J/g. In addition, this material can cope with relative large strains (50-100%). The SRI team incorporated an elastomer generator into a boot heel. The generator design is based on a membrane that is inflated by the heel strike. They achieved 0.8J/step (800mW)

using this device. This energy was harvested during a compression of 3mm of the heel of the boot onto which the device was mounted [29].

A key advantage in the construction of such devices is that they can use an existing shoe in order to implement their device, and by that reduce the need to wear a special device to generate the energy. The power output of these devices is relatively low, with a maximum of approximately 2W at normal walking speed. However, there are many applications (e.g., MP3 Player, PDA, cellular telephone) where this energy would be sufficient and this might be an excellent solution for this problem.

Knee

A device for the knee joint based on negative work of the muscles was proposed by Niu and colleagues, [30] and such a device has recently been developed by Donelan et al. [19] and Li et al. [31]. Their device comprises an orthopedic knee brace configured such that knee motion drives a gear train (113:1) through a unidirectional clutch, transmitting only knee extension motion to a DC brushless motor that serves as the generator (Figure 5). The device's weight was approximately 1.6kg. The generated electrical power was dissipated by a load resistor. This method generated 5W (from both knees using two devices) at 1.5m/s walking speed. The cost of harvesting the energy was an additional metabolic cost of 1 W. This additional cost is less than one-eighth of that for conventional human power generation (e.g., hand-crank generators as well as wind-up flashlights) would have required. However, there were some limitations to this device: 1) this device used only a small part of the motion of the knee (end of the swing phase) to generate energy. Where during the gait cycle the muscle net work in the knee joint is approximately 90% negative work which is approximately 34W. The current device harvests energy only at the end of swing phase, it has 65% efficiency, and two devices manage to harvest 5W during

walking at 1.5m/s. Based on this data we calculated the power difference between the current device and an ideal device (that could harvest all the negative work during walking). Power that is still available = (total power – current power output/ efficiency)*device efficiency = (33.5-5/0.65)x0.65= 16.8W. The main challenge in harvesting energy from the knee movement is that in order to harvest more energy the resistance to the motion as generated by the device will increase. This means that more of the motion controls will be done by the device and not by the human.

<< Figure 5 should be inserted about here>>

Method for energy conversion

So far we have reviewed human motion as a source of energy, as well as the current state of the energy harvesting technology. A key component of these energy harvesting devices is the method they use to convert the mechanical work to electricity. The main technologies used are: piezoelectric, Electro Active Polymers (EAP), and electrical induction generators. Piezoelectric materials generate a voltage when compressed or bent [32], and have been used mainly for heel strike devices. Their main advantage is that they are simple to incorporate into the shoe. However, due to the small displacement and high generated voltage, the power output of this technology is limited to approximately 100mW [30]. Electro Active Polymers (EAP) also generates electricity when under a mechanical stress; they have a low efficiency compared to magnetic machines and relatively high operation voltage that can make the electrical circuit complicated and expensive. Yet due to the excellent strain properties of EAPs when compared to piezoelectric, there is much more energy that could be harvested. Further, compared with magnetic materials, EAPs are much lighter and easier to shape. Therefore we conclude they are a good alternative for

biomechanical applications [33]**.** Magnetic machines are low in cost and have the highest conversation efficiency of the three methods. However, generally the higher efficiency levels are achieved at high speeds and in rotary implementations. Human motions are relatively slow, and as a result the application of electromagnetic energy conversion needs an addition of transmission to increase the rotation speed. While for the backpack the transmission added a small percentage to its total weight, in the knee device the transmission construction added approximately 650gr, which was 40% of the total weight of the device.

Moreover, when using a rotary magnetic-based generator, the input should ideally have a constant rotation direction and speed. However the human joint angles change speed and direction during the walking cycle; this adds more complexity to the use of rotary magnetic devices to harvest energy. Other directions for future research are the innovative design of magnetic machines that will reduce the need for high rotary speeds, improvement of the power density, and efficiency of energy harvesting using Elastomers.

Conclusions

Biomechanical energy harvesting technology is a new and interesting approach to producing energy for portable devices. We used biomechanical models to estimate the potential power output that could be harvested from each of the major human motions, and discussed the advantages and disadvantages of each motion. Further, a review of the state-of-the-art in these technology devices and types of energy conversion methods revealed that for heel strike devices the most promising technology seems to be Electro Active Polymers. This is mainly due to the low power–to-weight ratio, and that such devices actually produce energy in the amount of 0.8W, which is close to our estimation of a maximum of 2W during normal

walking. The backpack device achieved 7.4W at 6.5m/s, assuming 50% energy losses due to friction in the system and energy conversion loss. This power output is more than the available energy predicted by the model of required energy for redirecting the velocity of the mass at the end of each stride using the inverted pendulum mode. This suggests that more contributions to energy are required for carrying a backpack than only the redirection of the mass velocity (i.e part of the metabolic cost might be due to change in height of the centre of mass). The newest technology for energy harvesting is replacing the muscle work by regenerative braking, similar to that in hybrid cars. Theoretically, this method has 60W available when considering all the leg joints, and after typical conversion losses of 50% it is reasonable to believe that it could generate 25W at normal walking. This is much more than the other methods that aim to generate energy without increasing the metabolic cost. The main challenges that must be overcome to reach this goal are: first, the current knee device works only at the swing phase, not using all the phases of negative work during the gait cycle. The main challenge here is that the rotary magnetic base generator typically rotates at high speed (1000-10,000 rpm), while the human angular velocity for typical joint is in the order of 20 rpm. This mean a high gear ratio is required. Yet the higher the gear ratio, the more losses due to friction. Further, the human joint angles change speed and direction during the walking cycle, and ideally the generator should rotate in constant speed and direction. These demands, as well as the metabolic cost of to carrying additional weight of these devices, call for innovative and lighter design of these devices.

Another area that needs to be developed is the area of control. Currently these device use an on/off control with a load that, for a given motion, was determined by the generator, the gear ratio, and the effective electrical load. In order to be able to

harvest more energy there is a need to match the generator's and joint's angular and torque curves during the given motion. There are two ways to do so – first by constantly changing the gear ratio, and second, by changing the effective external electrical load. However, this high power output means that more of the motion control is done by the device and not by the human, and this should require a much more sophisticated control. Currently the knee harvester was tested during walking on a flat surface (treadmill), and used the angular velocity data to control the timing of harvesting. Yet when walking on a terrain that alters the gait pattern, angular data might not be sufficient to determinate the joint negative power phase.

In summary, biomechanical energy harvesting can be a clean, portable energy alternative for electronic mobile devices versus conventional batteries. This is especially true in areas where the power grid is not well developed, such as in third world countries. In addition, it could serve as a power source for medical devices such as prostheses with electrical motors and controllers, and exoskeletons, which could benefit from the development of this technology as well.

List of abbreviations

EAP -Electro Active Polymers

COH- coefficient of harvesting

Competing interests

NA

Authors' contributions

RR took the lead role in the biomechanical analysis, and the human physiology, mechanical design, figures design, and manuscript writing. AS contributed to the

aspects of mechanical design and control that are related to this study and to the writing.

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Figures

Figure 1: Ground reaction forces during execution of a single stride

Figure 2: Typical kinematics and kinetics during a walking cycle (subject mass=58 kg, speed 1.3 m/s; cycle frequency 0.9Hz. In data from [6]: Zero ankle angle is defined as 90 degrees between the shank and the foot; Zero knee angle is full extension of the knee (straight leg); Zero hip angle is thigh 90 degrees with the ground.

Figure 3: Walking as motion of an inverted pendulum

Figure 4: Suspended-load backpack for generating energy.

The pack frame is fixed to the body, but the load is mounted on the load plate, and is suspended by springs (red) from the frame (blue) (A). During walking, the load is free to ride up and down on bushings constrained to vertical rods (B). Electricity generation was accomplished by attaching a toothed rack to the load plate, which when moving up and down during walking, meshes with a pinion gear mounted on a geared dc motor, functioning as a generator, rigidly attached to the backpack frame [12].

Figure 5: Biomechanical Knee energy harvester [19]. (A) The device has an aluminum chassis and generator (blue) mounted on a customized orthopedic knee brace, totalling 1.6kg mass, with one worn on each leg. (B) The chassis contains a gear train that converts low velocity and high torque at the knee motion into the high velocity and low torque required for the generator operation, with a one-way clutch that allows for selective engagement of the gear train during knee extension only and no engagement during knee flexion. (C) The schematic diagram shows how a computer-controlled feedback system determines when to generate power using knee-angle feedback, measured with a potentiometer mounted on the input shaft. Generated power is dissipated in resistors. Rg, generator internal resistance; R_L, output load resistance; E(t), generated voltage.

Tables

Table 1: Work performed at the leg joints during a walking step normalized by the subject's mass. A1-3 are phases of work that are performed in the ankle joint, K1-4 are phases for the knee, and H1-3 are for the hip joint. Work represents the net summation of the joint muscles [14] and negative value represent negative work**.**

Work during the Phase (J/Kg)	Average (J/Kg)	Standard Deviation (J/Kg)
Ankle A-1	-0.0074	.0072
Ankle A-2	0.0036	0.0046
Ankle A-3	-0.111	0.042
Ankle A-4	0.296	0.051
Knee K-1	-0.048	0.032
Knee K-2	0.0186	0.026
Knee K-3	-0.047	0.015
Knee K-4	-0.114	0.015
Hip H-1	0.103	0.047
Hip H-2	-0.044	0.029
Hip H-3	0.090	0.027

Table 2: Summary of total work done by the muscles at each joint or segment of the body during the walking cycle.

Joint	Work [J]	Power [W]	Max torque [Nm]	Negative work	
				%	J
Heel Strike	1-5	2-20		50	1-10
Ankle	33.4	66.8	140	28.3	19
Knee	18.2	36.4	40	92	33.5
Hip	18.96	38	40-80	19	7.2
Centre of Mass	5.4,10**	10.8 ,20**			
Elbow	1.07	2.1	1-2	37	0.8
Shoulder	1.1	2.2	1-2	61	1.3

(*) Except for calculations for centre of mass and heel strike, all other calculations have been completed for an 80Kg human assuming a walking frequency of 1Hz per cycle (i.e., two steps). We chose to use 1Hz to simplify the calculation, since it is close to the 0.925Hz that was measured by Winter et al. [14].

** Energetic cost of transporting 20Kg payload using two models (walking frequency of 1Hz per cycle)

Additional files

Additional file 1 – Sample additional file title
Additional file descriptions text (including details of how to view the file, if it is in a non-standard format).

Additional file 2 – Another sample additional file title
Additional file descriptions text (including details of how to view the file, if it is in a non-standard format).

Figure 1

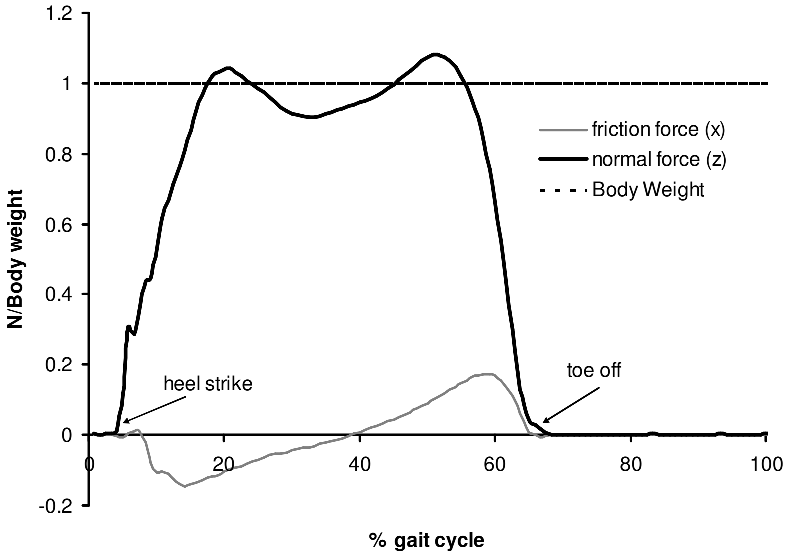


Figure 1

Figure 2

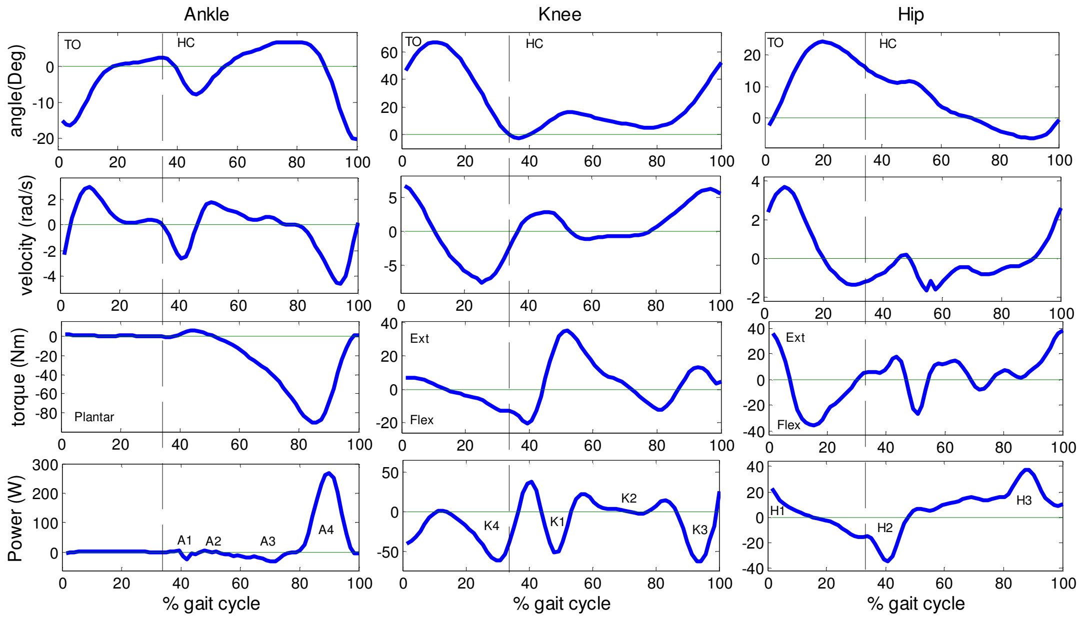


Figure 2

Figure 3

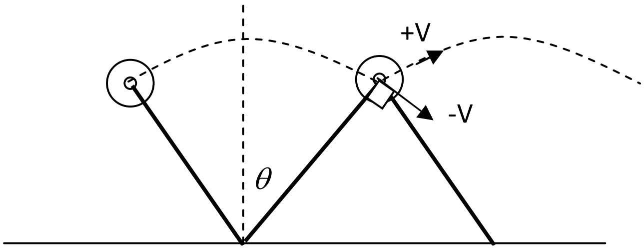


Figure 4

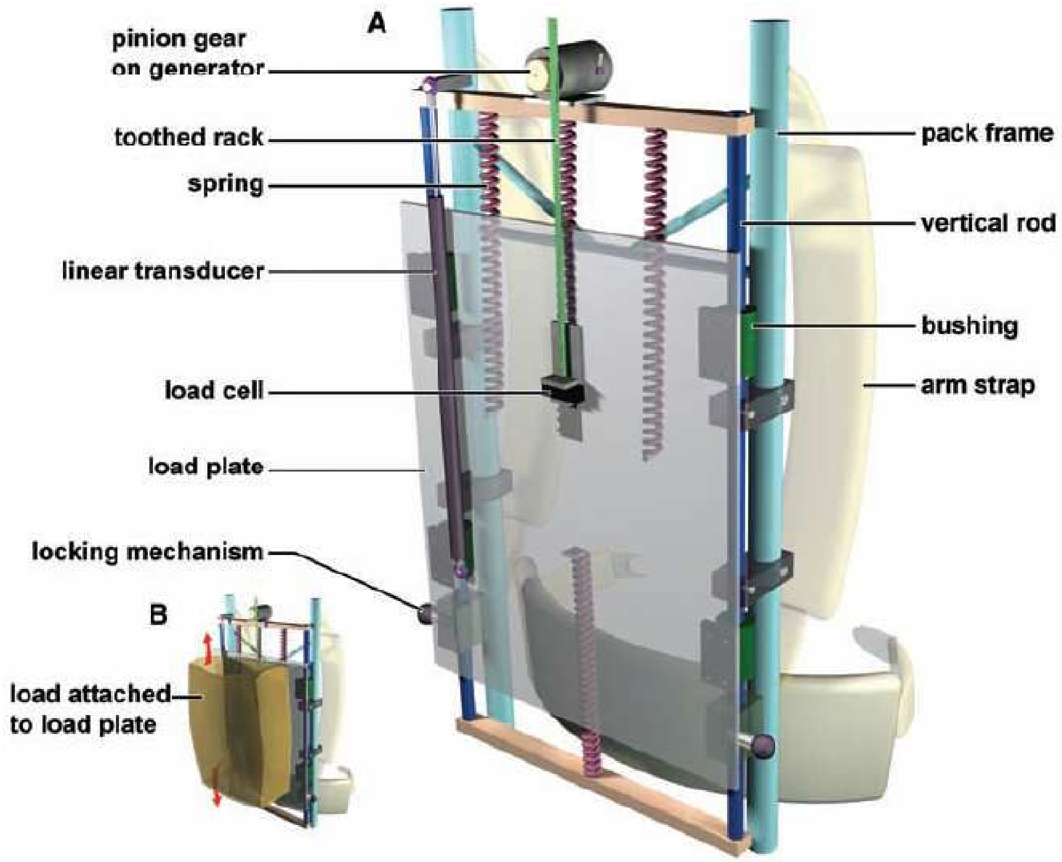
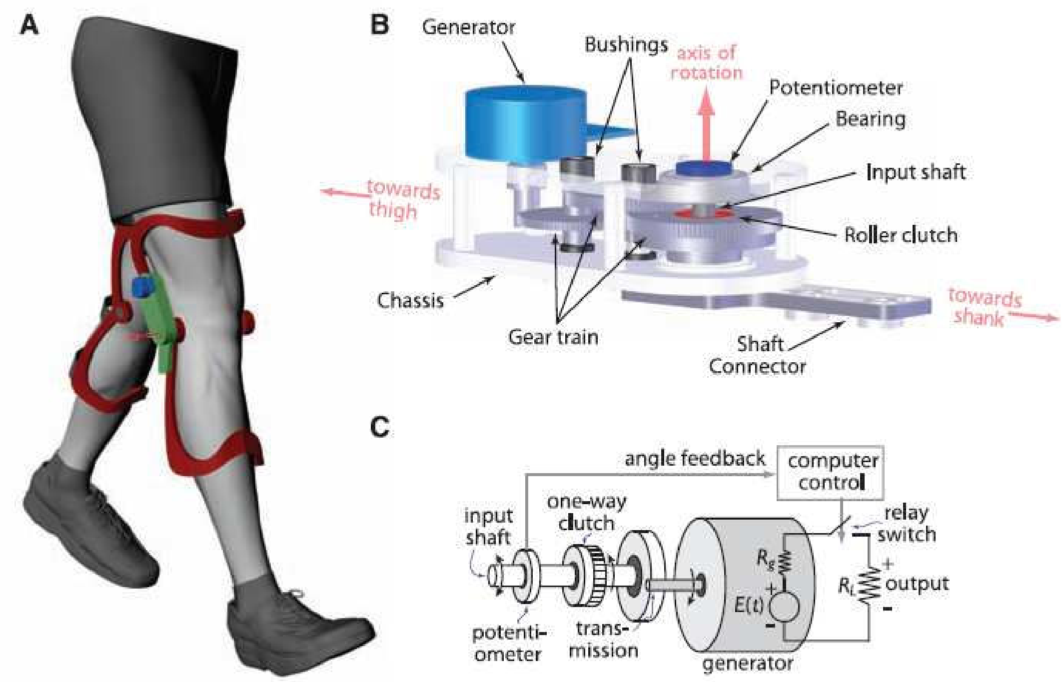

A
pinion gear
on generator
toothed rack
spring
linear transducer
load cell
load plate
locking mechanism
pack frame
vertical rod
bushing
arm strap
B
load attached
to load plate

Figure 5



A
B
Generator
Bushings
axis of rotation
Potentiometer
Bearing
Input shaft
towards thigh
Roller clutch
Chassis
Gear train
Shaft Connector
towards shank
C
angle feedback
computer control
input shaft
one-way clutch
relay switch
R_g
R_L
output
$E(t)$
potenti-ometer
trans-mission
generator